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End mill tools integration in CNC machining for rapid manufacturing processes: simulation studies

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Computer numerical controlled (CNC) machining has been recognized as a manufacturing process that is capable of producing metal parts with high precision and reliable quality, whereas many additive manufacturing methods are less capable in these respects. The introduction of a new layer-removal methodology that utilizes an indexing device to clamp the workpiece can be used to extend CNC applications into the realm of rapid manufacturing (CNC-RM) processes. This study aims to improve the implementation of CNC machining for RM by formulating a distinct approach to integrate end mill tools during finishing processes. A main objective is to enhance process efficiency by minimizing the staircasing effect of layer removal so as to improve the quality of machined parts. In order to achieve this, different types of end mill tools are introduced to cater for specific part surfaces during finishing operations. Virtual machining simulations are executed to verify the method and the implications. The findings indicate the advantages of the approach in terms of cutting time and excess volume left on the parts. It is shown that using different tools for finishing operations will improve the capabilities of CNC machining for rapid manufacturing applications.

Keywords: end mill tools; CNC machining; rapid manufacturing

1. Introduction

In machining processes, it is crucial to ensure good surface finish quality as this will influence the performance of machined parts and production costs (Davim, 2001). Improving surface finish has become a major concern particularly in rapid manufacturing processes where the objective is to achieve final geometry directly. A major consideration in rapid manufacturing processes is that planning time needs to be substantially reduced so that overall time from design to finished part is also reduced. In additive processes (AM), relatively long fabrication times are compensated by the limited planning time required. In traditional computer numerical controlled (CNC) the opposite situation exists, and whilst machining can be very rapid, the planning process may be complex and time-consuming. In trying to use CNC for rapid applications, the main effort is in maintaining a simple approach to planning whilst possibly sacrificing some of the available machining efficiency.

An approach that has some of the advantages of additive manufacturing involves the use of an indexable fourth axis device to hold and clamp the workpiece onto the table

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of a three-axis CNC milling machine (Figure 1). This approach allows a layer-removal process to take place at various rotations about one axis and complex shapes and features can be created by layer-based removal of material (Frank, Wysk, & Joshi, 2006). The indexable device permits rotation about one axis while also clamping the workpiece. Layers are removed from several orientations to reveal all surfaces of the part without refixturing (Frank et al., 2006). Determination of the necessary orientations is central to the process and this is achieved by visibility algorithms (a minimum set of orientations are sought where the surfaces are 'visible' from the direction of the tool).

Within each orientation, roughing and finishing operations are performed sequentially using different tool sizes and machining parameters. Machining starts with the first roughing operation that cuts until the furthest possible surface is reached or the workpiece is fully cut (Frank, 2007). Then, finishing operations are executed no further than the central axis of the cylindrical workpiece. In order to reduce effort in the planning tasks, feature recognition on machined parts is avoided. Therefore, the selection of a cutting tool becomes straightforward and is based on the smallest diameter and a flat end mill tool is most likely to be selected.

Despite the effectiveness of reducing complexities in the planning phase, the use of a single end mill tool in finishing processes leads to several drawbacks. First, due to the geometry of flat end mill cutters, a staircasing effect is visible on part surfaces particularly on contours and non-flat regions. This effect still can be seen even if very small cutting layer depths are adopted (Frank, Joshi, & Wysk, 2002). In addition, using small cutting depths will obviously increase cutting times considerably. Another limitation can be seen in the assessment of tool accessibility of part features. Analysis that focuses on machinability has resulted in some uncut material being left on the part due to inaccessibility of the cutting tool (Li & Frank, 2006) and inevitably this will affect dimensional accuracy. Figure 2 illustrates potential non-machined regions generated on a toy jack part. To date, no specific method has been developed to cater for the integration of different end mills in rapid machining processes. Therefore, this study attempts to show that using different end mill tools in finishing operations can improve surface finish by reducing the excess volume left on the parts. The next section of the paper will review the previous approach in cutting tools selection for CNC-RM processes. A methodology to integrate end mill tools is then described considering the implications for process planning and cutting operations. A framework for the simulation studies is established that is later used to generate the results to validate the proposed method. The findings

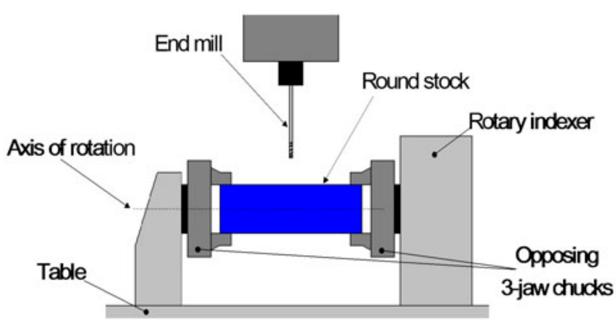


Figure 1. Setup for CNC-RP (Frank, Wysk, & Joshi, 2004).

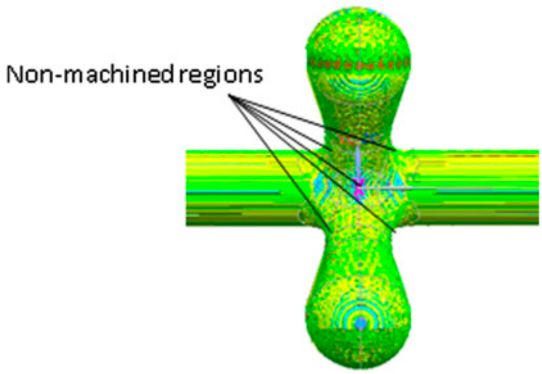


Figure 2. Possible non-machined regions using a flat end mill tool (Li & Frank, 2006).

are described further to highlight the achievements and limitations of the approach before drawing conclusions.

2. Cutting tools and machining operations

Initially, due to the objective of simplifying process planning, only a single cutting tool with the smallest possible diameter is used in CNC machining for rapid prototyping processes (Frank, 2003). Since the visibility analysis is based on 2D cross-sectional layers of part geometries, a flat end mill tool is usually selected to finish cut the part. Consequently, the machined parts exhibit the same staircase effect as presented in most of the AM processes. Figure 3 shows the staircase effect formed on contoured surfaces of a part. However, CNC machines are capable of reducing the layer thickness down to 0.0127 mm. Therefore, the step appearance is minimized within an acceptable range for making prototypes. From a planning perspective, the use of a single cutting tool has generalized the cutting areas to cover all surfaces in each orientation. This avoids any feature recognition tasks during machining process. Only one cutting operation is performed in each orientation that considerably reduces the number of operations and planning complexities. However, a small cutting tool requires more passes, which will result in longer machining times. Besides, the removal of thin layers is inefficient especially when the bulk of the material needs to be removed during early phases of machining.

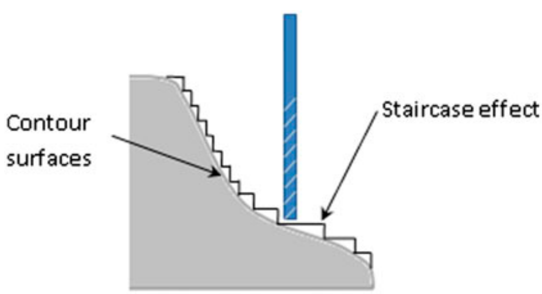


Figure 3. Staircase effect presented on contoured surfaces.

These considerations tend to restrict the capabilities of CNC machining even if some level of automation is embedded in the process planning.

Due to the inefficiency caused by a single cutting tool, later developments suggest the use of different tool sizes to handle roughing and finishing operations (Frank, 2007). As a result, roughing operations utilize larger tool diameters selected based on the size of the workpiece. Hence, high volumes of material can be removed during roughing operations whilst leaving sufficient material for finishing processes. Meanwhile, the approach of selecting the smallest tool diameter remains the same for executing finishing operations. This allows the cutting tool to reach all features presented on the part. Both roughing and finishing operations employ the same cutting areas. Thus, within one cutting orientation, two different toolpaths are developed and this directly increases the number of machining operations. Additionally, tool changes are required in each orientation and can be carried out through automated systems built into the CNC machine. This combination of different tool sizes based on roughing and finishing operations succeeds in enhancing the application of CNC machines in producing parts rapidly.

The introduction of different cutting tool sizes has resulted in a further study that attempts to assist in the selection of a proper combination of end mill tool sizes for roughing and finishing operations. Different tool sizes possess different abilities in removing the material and shaping the part. Large tools are capable of removing more material in shorter time, but are restricted in accessing small cutting regions. To the contrary, small tools have much improved accessibility but very inferior rate of material removal. Therefore, an appropriate combination of tool sizes is necessary to machine the workpiece effectively. The region that is accessible to different tool sizes can be calculated through the Tool Access Volume (TAV) method. Then, the analysis is extended to identify appropriate tool selection and sequencing by using a method known as Relative Delta Volume Clearance (RDVC) (Lim, Corney, Ritchie, & Clark, 2001). Based on information gained from these analyses, tool sizes and a set of cutting orientations can be identified by applying a genetic algorithm technique (Renner, 2008). Accordingly, the machining times are substantially reduced by using carefully selected combinations of tool sizes.

A recent study has proposed another approach to further improve the machining operations in CNC-RM (Osman Zahid, Case, & Watts, 2014). It was successfully carried out by manipulating the orientations for roughing operations. Instead of performing roughing and finishing operations using the same set of orientations, rough cuts were extracted and performed through another set of orientations. This set of orientations was based on a combination of four cutting orientations, 0–90–190–270°. A customized programme was developed to simulate the cutting process and propose efficient cutting directions. This method reduced the required cutting tool depth during roughing operations for avoidance of tool breakage. Since roughing and finishing operations are based on different sets of orientations, tool changes occur only once throughout the process. The time spent on roughing operations frequently increases, but it was found that this resulted in a reduction of total machining time.

Over the years, much research has been aimed at reducing machining time by manipulating cutting parameters as a part of process planning (Bouzid, 2005; Lavernhe, Tournier, & Lartigue, 2008; Palanisamy, Rajendran, & Shanmugasundaram, 2007). A good surface finish with low machining time can be obtained through the proper selection of machining parameters (Bharathi Raja & Baskar, 2012). The prominent parameters to be controlled are cutting speed, feed rate and depth of cut. Based on a multiple regression model, a previous study indicated that the depth of cut was the most influential parameter in determining the level of surface roughness achieved (Agarwal, 2012). Therefore, it is undeniable that cutting parameters are among the major factors that influence surface quality and machining time. However, in CNC-RM applications, the aim is to rapidly generate machining operations that reflect the planning and execution stages. Optimizing cutting parameters would require the handling of a large number of variables, and this tends to complicate the planning tasks and limits the level of automation that can be adopted in the planning stage. Therefore, the study conducted here integrates different end mill tools and observes the implications for machining time and surface quality. However, efficient cutting parameters suggested from previous studies could still be incorporated during the planning stage. Based on specific materials and tool sizes, a set of efficient parameters could be incorporated using decision-making tools in the development of machining plans.

Generally, the developments in selection of cutting tools and machining operations have enhanced the ability of CNC machining for rapid processes. The time required to machine parts has been substantially reduced with the introduction of roughing and finishing operations, appropriate tool size combinations and different rough cut sets of orientations. All these have enhanced the application of end mill tools in CNC machining, particularly for rapid manufacturing. However, far too little attention has been paid to the geometries of the end mill tool while developing the machining operations. Hence, there are no clear guidelines on how to combine the different tool geometries in the processing steps of CNC-RM. Nevertheless, several studies have strongly addressed the significance of cutting tool geometries on the level of quality achieved in the machining process (Patel, 2010; Reddy & Rao, 2005). Even if cutting can proceed at a very small depths of cut, neglecting the tool geometries tends to constrain the abilities of CNC machining in producing high quality parts. Therefore, considering the rapid manufacturing application, integrating different types of end mill tools is thought to be an approach to fulfil the quality requirements of end-use products.

3. Methodology

In attempts to implement CNC machining for rapid manufacturing processes, finishing tool selection is strictly defined based on the smallest diameter single end mill tool. This approach minimizes the tasks required in the planning phase and realizes the rapid generation of machining operations. Nevertheless, there is an implication for part quality as a single end mill tool is not capable of catering for a wide range of part surfaces. Therefore, integrating different end mill tools is a possible way of resolving the problem, but the guidelines must be clearly defined so that process planning can be handled effectively. Several important tasks are identified including separation of cutting regions and the types of end mill tool selected.

3.1. Cutting tools and surface classification

In the CNC-RM approach, finishing operations are executed through predetermined orientations and aim to shape the material completely. Hence, this process cuts the material with very small depths of cut to obtain a fine surface finish. Previous developments have implemented different cutting tools to finish cut parts built by welding process through a layer deposition method (Akula & Karunakaran, 2006). However, this approach utilized various type of tools and several surface categories, and seems impractical as it tends to complicate the planning tasks. However, some modifications to minimize and eliminate irrelevant setups will help to adopt this method in CNC-RM processes.

From one particular cutting direction, surfaces of the part can be classified into flat and non-flat surfaces. A flat surface is defined as a surface that is perpendicular to the cutting tool direction whereas the rest of the surfaces are categorized as non-flat surfaces. These classifications allow specific cutting tools to be assigned to machine the part effectively. Therefore, one orientation will perform up to two cutting operations if both types of surface are present. The first areas that will be cut are the flat surfaces using a flat end mill cutter. The process continues by machining non-flat surfaces using a ball nose end mill. Based on Figure 4, assuming cutting starts at 0^o cutting orientation, the tool is engaged with the workpiece from ZC direction. In this particular direction, the dark areas represent flat surfaces that are perpendicular to the cutting tool direction. The first finishing operation is performed on this surface using a flat end mill tool. Then, the CNC machine replaces the current tool with a similar-sized ball nose end mill. This tool is used to machine the other surfaces shown as light grey areas on the part.

Generally, there are three common end mill tools (Figure 5) that differ based on the shapes of the tool tip. These are flat, bull nose and ball nose end mills. In this study, only two tools are selected to be utilized in finishing operations. This selection is expected to greatly reduce the complications for process planning as only two variables are present instead of three. A flat end mill is capable of machining plane surfaces with a minimum scallop size compared to other tools (Elber, 1995; Ryu, Choi, & Chu, 2006). Therefore, this is exactly the right tool to cut the flat surfaces classified on parts. The second selection utilizes a ball nose tool to cater for non-flat surfaces. Based on previous studies, the capabilities of this tool in handling sculptured surfaces are proven and high-quality surface finish can be produced (Chen, Huang, & Chen, 2005; Chen & Shi, 2008; Vijayaraghavan, Hoover, Hartnett, & Dornfeld, 2008). Moreover, this tool can be easily guided to engage with part surfaces and produces simpler NC code for machining (Chen & Shi, 2008). Meanwhile, a bull nose end mill is capable of removing high volumes of material with efficient machining times (Patel, 2010). But, due to the tool tip geometry, there is limited access to certain part features and this can result in

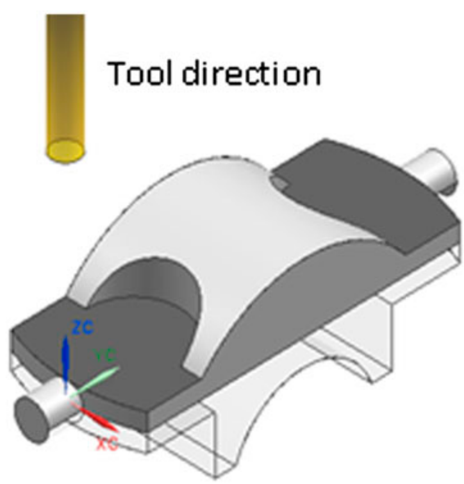


Figure 4. Classification of flat and non-flat surfaces in one cutting direction.

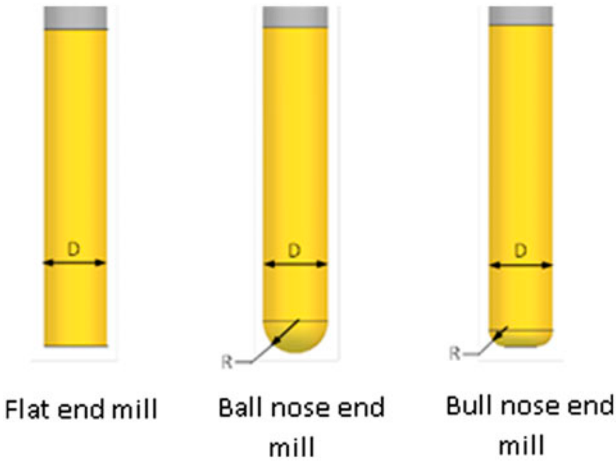


Figure 5. Three common shapes of end mill tool (Engin & Altintas, 2001).

high volumes of excess material. This limitation is shown in Figure 6. Therefore, in this study, only flat and ball nose end mills are selected for cutting tool integration in the CNC-RM processes.

3.2. Machining and verification processes

The introduction of different end mill tools requires a revision of the machining parameters, especially the cutting levels. Similar to roughing operations, finishing operations continue until the central axis of the cylindrical workpiece is reached. However, this is only applicable if a flat end mill tool is used in the operation. In the case where both tools are used, the ball nose cutter requires extended cutting levels to completely remove the remaining material. This is critically important for a part that contains closed regions that only permit tool access in limited directions. Figure 7 illustrates the situation where there is excess material due to there being insufficient cutting levels. Therefore, the cutting levels for a ball nose tool are extended by at least half the cutting tool diameter from the centre of the workpiece. Other parameters such as cutting feed and spindle speed are dependent on the diameter of the end mill tool. The finishing

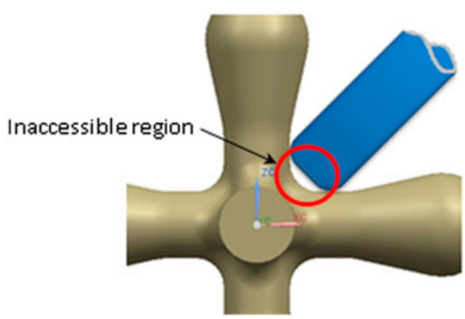


Figure 6. Restricted accessible regions for bull nose end mill tool.

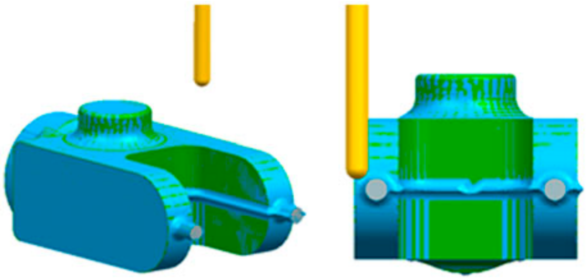


Figure 7. Remaining uncut materials left by ball nose end mill tool.

operations in this study employ the same tool diameter regardless of the type of tool used. Hence, both share the same value of spindle speed and feed rate. In this study, spindle speed and feed rates were determined based on the size of the cutting tools. The parameters are proposed by the CAD/CAM software itself and are not necessarily optimum cutting parameters. Depending on the models, depths of cut ranged between 1 and 1.5 mm for rough machining and 0.1 and 0.3 mm for finishing operations.

The simulation analysis was carried out with NX 7.5 software using the manufacturing application. A series of machining operations were created and the software used to estimate machining time to fabricate the parts. In order to calculate the excess volume left, the analysis was extended by using CGTech VERICUT ® 7.2.3 (CGTech, 2012). Recently, this software has been interfaced to NX which provides convenient access to run the simulation once operations have been created. There are several pre-processing steps while calculating the excess volume. First, the machining operations are translated into a cutter location source file (.clsf). Then, the file is run on VERICUT® software to simulate the cutting operations. Once completed, the 'X-caliper' tool is activated to

Table 1. Results for drive shaft and knob model.

Approach Criteria		Drive shaft		Knob	
		Approach 1	Approach 2	Approach 1	Approach2
Machining time	h:min:s	04:13:20	04:02:35	03:50:09	03:52:40
Finishing time		02:38:30	02:28:39	02:44:49	02:27:16
Non-cutting time		00:16:58	00:16:08	00:09:11	00:10:20
Roughing time		01:17:52	01:17:48	01:15:04	01:15:04
Cutting orientations		90–180–280–0–32–180–0°	90–180–280–0–32–180–0°	90–180–280–0–180–45–315°	90–180–280–0–180–45–315°
Machined volume	mm^3	150,273.23	150,432.83	112,946.97	113,203.60
Current part volume		53,244.05	53,084.45	21,660.63	21,403.91
Excess volume		514.82	355.22	527.99	271.27

obtain volumetric information. This includes stock volume, machined volume and current part volume. Prior to that, the machined part volume is calculated by a 'measure bodies' tool available in the NX system. All this information is gathered and the excess volume is calculated by subtracting the current part volume from the machined part volume. Finally, the results obtained are used to evaluate the effectiveness of integrating end mill tools in the machining processes.

4. Results and discussion

The simulation studies were conducted using different models including drive shaft, knob, salt bottle and toy jack models. Figure 8 illustrates the models adopted for the simulation studies. To visualize the implications of the suggested approach, similar cutting operations relying totally on the use of a flat end mill tool were developed. Therefore, Approach 1 was based on a process that utilized a single flat end mill whereas Approach 2 represented the method developed in this study that integrates different cutting tools. In this study, machining parameters were determined based on the size of the cutting tools. Since there are two types of operations (roughing and finishing), two sets of cutting parameters were involved. Meanwhile in the finishing operations, two different tools are introduced (flat and ball nose end mill). However, the machining parameters are similar since only one size of cutting tool is used. It is important to note that all the machining parameters are constant between Approach 1 and 2. Thus, the improvements gained from this study totally relied on the implication of different end mills during finishing operations. The study is not meant to validate the optimum cutting parameters, but the values could be adopted in the planning stage.

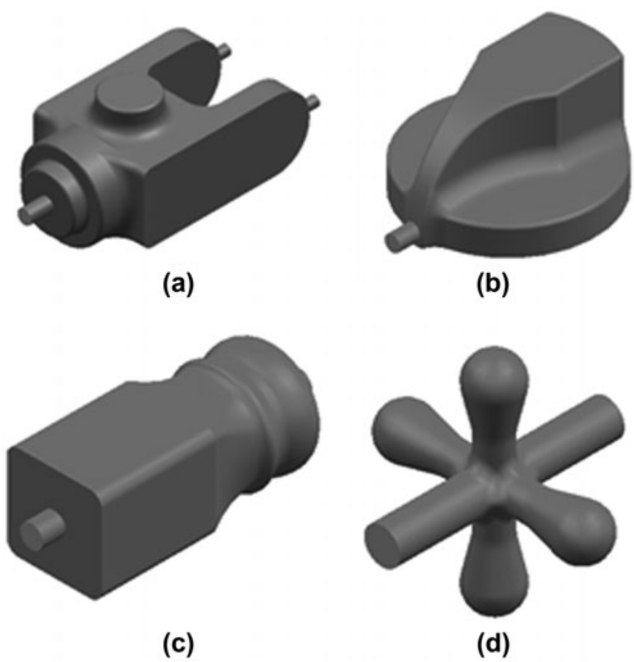


Figure 8. (a) Drive shaft, (b) knob, (c) salt bottle and (d) toy jack model.

There are two main evaluation criteria that are based on machining time and excess volume. Tables 1 and 2 summarize the results produced from simulation studies. Machining time is recorded in (h:min:s) format and volume information is in mm^3. The amount of material removed from the workpiece is presented as machined volume in the table. Part and stock volumes are calculated earlier based on the virtual models. It is apparent from these tables that there are considerable differences between Approaches 1 and 2. Out of the four models, three indicate a reduction of cutting time by implementing the approach developed in this study. Interestingly, all models achieved low excess volumes once different cutting tools were used in finishing operations. Assigning specific tools to particular surfaces, the ranges of excess volume reduce from 0.9–3.3% down to 0.7–1.6% of the total part volume.

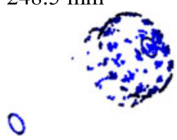
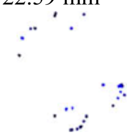
4.1. Implications for machining time

Data gathered in the tables clearly indicate the benefits of implementing different cutting tools in CNC-RM processes. The majority of the models studied show a decreasing trend of machining time compared to a single tool approach. Finishing cutting times contribute most of the savings. This signals the effectiveness of cutting tools removing material on assigned surfaces. Depending on part geometries, cutting times differ from 2 min up to 11 min. For example, results for the drive shaft model in Table 1 indicate that the current method in Approach 2 manages to reduce machining time by about 11 min compared to Approach 1. Nonetheless, some models show only a small reduction of machining time such as the toy jack model. In this model, only ball nose tools were used as only non-flat surfaces were present on the part. For a medium production run, this reduction might still be important in minimizing cost and time. Oppositely, the knob model indicated a slightly longer machining time compared to Approach 1. The variety of flat and non-flat surfaces present on the part are possibly the main factors influencing cutting time.

Table 2. Results for salt bottle and toy jack model.

Approach Criteria		Salt bottle		Toy jack	
		Approach 1	Approach 2	Approach 1	Approach 2
Machining time	h:min:s	04:32:02	04:23:26	03:25:22	03:21:42
Finishing time		02:38:44	02:29:33	02:16:04	02:12:44
Non-cutting time		00:11:57	00:12:28	00:14:06	00:13:44
Roughing time		01:41:21	01:41:26	00:55:12	00:55:12
Cutting orientations		0–90–190–270–45–180–270°	0–90–190–270–45–180–270°	50–140–240–320–49–140–228–320°	50–140–240–320–49–140–228–320°
Machined volume	mm^3	76,676.80	76,845.85	109,662.15	109,792.30
Current part volume		34,499.39	34,330.33	7769.86	7639.71
Excess volume		417.56	248.5	252.74	122.59

Table 3. Excess materials distribution based on studied models.

Drive shaft		Knob	
Approach 1	Approach 2	Approach 1	Approach 2
514.82 mm^3	355.22 mm^3	527.99 mm^3	271.27 mm^3
			
Salt bottle		Toy jack	
Approach 1	Approach 2	Approach 1	Approach 2
417.56 mm^3	248.5 mm^3	252.74 mm^3	122.59 mm^3
			

The simulation studies adopted different sets of orientations for roughing and finishing operations as proposed from previous research (Osman Zahid et al., 2014). Therefore, integrating different end mill tools did not add to the number of orientations, but it increased the number of operations and tool changes. The presence of flat and non-flat surfaces in one cutting orientation will require both end mill tools and one tool change operation. Taking the salt bottle as example, there are two orientations consisting of flat and non-flat surfaces. Hence, four finishing operations are required within the two cutting directions. Meanwhile, in a single tool approach (Approach 1), only one finishing operation is needed in each orientation and this is quite straightforward compared to Approach 2. However, considering the effectiveness of material removal, it is worthwhile integrating the cutting tools.

4.2. *Volume of excess materials*

Previous studies have validated the capabilities of ball nose cutters on sculptured surfaces. Hence, assigning the tools based on flat and non-flat surfaces manages to minimize the excess volume on parts. Surprisingly, simulation results consistently indicate that excess volume was reduced for all models studied. Some models show a considerable reduction. For instance, excess volume for the knob model decreases dramatically from 527 mm^3 down to 271 mm^3. In CNC machining, uncut materials can be reduced by modifying cutting parameters in finishing operations including depth of cut, number of passes, feed rates and speed. However, in the CNC-RM approach, all these parameters remain constant except for the type of cutting tools used. Therefore, the achievements of this study show that the cutting tool combination is the main factor that influences the results.

Furthermore, the implications can be visualized by analysing the material distribution diagram as shown in Table 3. Comparing Approach 1 and 2, it can be seen that most of the excess material on non-flat surfaces of the part have been reduced. This indicates that the ball nose cutter effectively minimizes the staircasing effect. Keeping the flat end mill cutter to machine flat surfaces is useful in overcoming the weakness of ball nose tools.

5. Limitations and future work

Using multiple end mill tools in finishing operations manages to greatly reduce the excess volume left on the machined parts. The results of simulation studies indirectly portray the benefits of the approach in terms of surface quality. But, observation of the cutting simulations has revealed a limitation in shaping the sacrificial support of the part. If the support structure is connected to a flat vertical surface, a ball nose end mill faces a difficulty in completely shaping the structure. An excess volume (fillet shape) is created on the edge of the support and part. This problem is shown in Figure 9. On the other hand, a flat end mill is capable of forming the sharp edge, but is limited to areas that are perpendicular to the cutter direction. Excess volume will still be present in the rest of the connection area. Currently, the only way to minimize the problem is by using the smallest possible end mill tool during finishing processes. Larger tools will increase the excess volume and cause more work at the post-processing stage.

In real applications, several variations can be expected on the method proposed in this study. First, the rate of material removal is highly dependent on the size of cutting tools adopted in roughing and finishing processes. The implications can be seen based on accessibility and machining time. Selection of the smallest cutting tool in finishing operations will guarantee the accessibility, but machining time will probably be extended. Using optimization tools like TAV and RDVC that have been discussed earlier could be helpful in reducing the variations. Another factor that will cause variation between simulation and real machining is process interventions. In the simulation study, the estimated cutting time represents the complete operation including cutting and non-cutting time, but times for tool changes and workpiece rotations were not considered. If both are fully automated, it would have less impact on the cutting time. However, if the operations are carried out manually, which requires the machine to stop, then the estimated time is likely to be extended. For this reason, it is highly recommended that CNC-RM operations are executed in an automated manner.

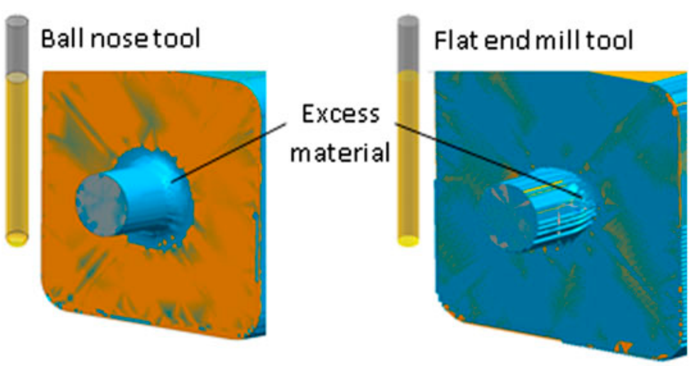


Figure 9. Excess material formed at the edge of sacrificial support.

The integration of cutting tools has benefited the production stage of the CNC-RM, but, it affects the planning stage as more variables need to be handled. Previously, process planning in CNC machining restricted implementation in RM as it involves many manual tasks and is highly dependent on human skill (Anderberg, Beno, & Pejryd, 2009; Relvas & Simoes, 2004). However, a recent development in CAD/CAM has introduced several features that can be used to effectively handle the process planning tasks (Agrawal, Soni, & Dwivedi, 2013). Therefore, an assisting tool can be developed to integrate the cutters while constructing the machining operation in the system and make it adaptable to any kind of part features. On the other hand, the identification of flat and non-flat surfaces within the cutting orientations needs to be performed correctly to ensure the right end mill tools are selected. Flat surfaces are not only the horizontal and vertical surfaces of the CAD model, but, depending on cutting direction, inclined surfaces can also be considered as flat surfaces if they are perpendicular to the direction of tool movement. Considering these issues, the medium of communication between the user and the system must be preserved to assist decision-making during process planning. To realize this, customized programming tools and computerized systems can be implemented in the CNC-RM process plan.

6. Conclusion

This simulation study has revealed the advantages of using different cutting tools in finishing operations particularly for CNC-RM processes. The present study was designed to improve part quality by reducing uncut material left after completion of machining. Generally, using different tools to cater for flat and non-flat surfaces is an effective way to reduce excess volume. Furthermore, machining times also can be reduced depending on part geometries. In order to visualize the implications, the results were compared to a previous method that adopted a single flat end mill tool throughout the cutting operations. Distinctly, the comparisons show the method developed in this study is capable of enhancing part quality and appearance. Further studies could focus on integrating this approach into CNC-RM process planning. The surface classification task needs to be handled carefully so that it will not complicate the planning task. Also, further verification is still required through machining experiments so that real parts can be fabricated and analysed completely. In the simulation studies, the excess volume was a key indicator to determine the surface quality of the part. However, in real machining operations, the surface quality needs to be examined through roughness analysis.

Disclosure statement

No potential conflict of interest was reported by the authors.

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